

# Single top quark production and $V_{tb}$ at the Tevatron

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Single top quark production via the electroweak interaction was observed by the D0 and CDF collaborations at the Tevatron proton-antiproton collider at Fermilab. Multivariate analysis techniques are employed to extract the small single top quark signal. The combined Tevatron cross section is  $2.76^{+0.58}_{-0.47}$  pb. This corresponds to a lower limit on the CKM matrix element  $|V_{tb}|$  of 0.77. Also reported are measurements of the  $t$ -channel cross section, the top quark polarization in single top quark events, and limits on gluon-quark flavor-changing neutral currents and  $W'$  boson production.

## 1 Introduction

The observation of single top quark production via the electroweak interaction was first reported in 2009 by the DØ<sup>1</sup> and CDF<sup>2</sup> collaborations. Both experiments reported observation at the five standard deviation level and measured the CKM matrix element  $V_{tb}$ <sup>3,4</sup>. Their results were also combined<sup>5</sup>. Here we present the two observation analyses, their combination, and several searches for new physics in the single top quark final state.

## 2 Cross section measurement

Single top quark production proceeds via the  $t$ -channel exchange of a virtual  $W$  boson between a light quark line and a heavy quark line or the  $s$ -channel production and decay of a virtual  $W$  boson. The single top quark observation analysis from the DØ collaboration was done in the lepton (electron or muon) +jets final state using  $2.3 \text{ fb}^{-1}$  of data. The CDF collaboration utilized both the lepton+jets final state with  $3.2 \text{ fb}^{-1}$  of data and the missing transverse energy ( $\cancel{E}_T$ ) +jets final state with  $2.1 \text{ fb}^{-1}$  of data<sup>6</sup>. DØ later added the  $\tau$  lepton +jets final state<sup>7</sup>.

The single top quark final state contains a lepton and a neutrino from the  $W$  boson decay, a  $b$  quark from the top quark decay and an additional light quark ( $t$ -channel) or  $b$  quark ( $s$ -

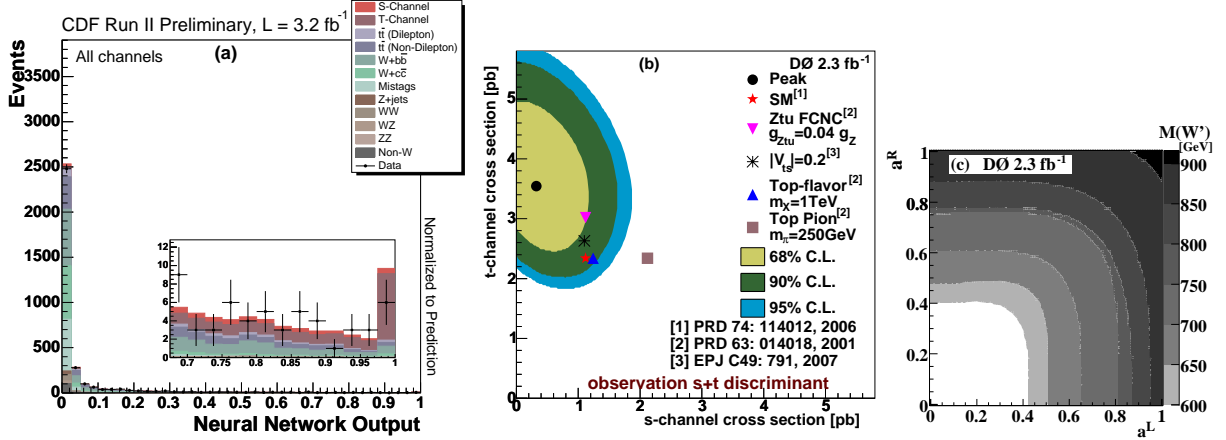


Figure 1: (a) The combination neural network output of the CDF single top quark observation, (b) the posterior probability density of the DØ single top quark observation as a function of the  $s$ -channel and  $t$ -channel cross sections, and (c) limit on the mass of the  $W'$  boson as a function of the left-handed and right-handed  $W'$  boson coupling.

channel). The event selection for all analysis channels requires large  $\cancel{E}_T$  and two to four jets (DØ) or two to three jets (CDF), at least one of which is  $b$ -tagged. The analysis channels differ in the lepton requirement from the  $W$  boson decay. The channels with the largest sensitivity require exactly one electron or exactly one muon. CDF has an additional channel requiring no reconstructed lepton, and DØ has an additional channel requiring a reconstructed  $\tau$  lepton. In total, about 13,000 events are selected by the two collaborations with an expected SM signal of about 550 events.

The expected single top quark signal is small compared to the statistical uncertainty and the uncertainty on the background prediction. Thus, multivariate analysis methods are employed to extract the single top quark signal. DØ and CDF both use several different multivariate methods which are then combined into one filter. The output of the combined single top filter for the CDF experiment is shown in Figure 1(a). The single top quark signal is clearly visible above the backgrounds in the high-discriminant region.

Both DØ and CDF observed single top quark production at the five standard deviation level. The measurement of the single top quark production cross section from DØ is  $3.94 \pm 0.88$  pb, and the measurement from CDF is  $2.3^{+0.6}_{-0.5}$  pb. Figure 1(b) shows the DØ Bayesian posterior probability density distribution as a function of both the  $s$ -channel and the  $t$ -channel cross sections. Also shown are the SM expectation<sup>9</sup> and several new physics models that affect single top quark production<sup>10,11</sup>. The combined Tevatron cross section is  $2.76^{+0.58}_{-0.47}$  pb<sup>5</sup>.

The single top quark production cross section measurement also provides a measurement of the CKM matrix element  $V_{tb}$ , without requiring any assumptions about the number of generations or the unitarity of the CKM matrix<sup>3,4</sup>. The combined Tevatron measurement of  $|V_{tb}|$  is  $0.88 \pm 0.07$ , with a lower 95% confidence level limit of 0.77, using a theory cross section of  $\sigma_{s+t}^{\text{theory}} = 3.46|V_{tb}|^2$  by Kidonakis<sup>8</sup>.

The DØ collaboration isolated the  $t$ -channel mode of single top quark production by training multivariate filters for this signal alone. The result is first evidence for single top quark production in the  $t$ -channel at the 4.8 standard deviation level. The corresponding  $t$ -channel production cross section, making no assumptions about the  $s$ -channel cross section, is  $\sigma_t = 3.1 \pm 0.9$  pb<sup>12</sup>.

The top quark decay width and lifetime is extracted from a combination of this measurement and a measurement of the top quark decay branching ratio<sup>14</sup>. The measured width is  $\Gamma_t = 1.99^{+0.69}_{-0.55}$  GeV, which corresponds to a top quark lifetime of  $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$  s.

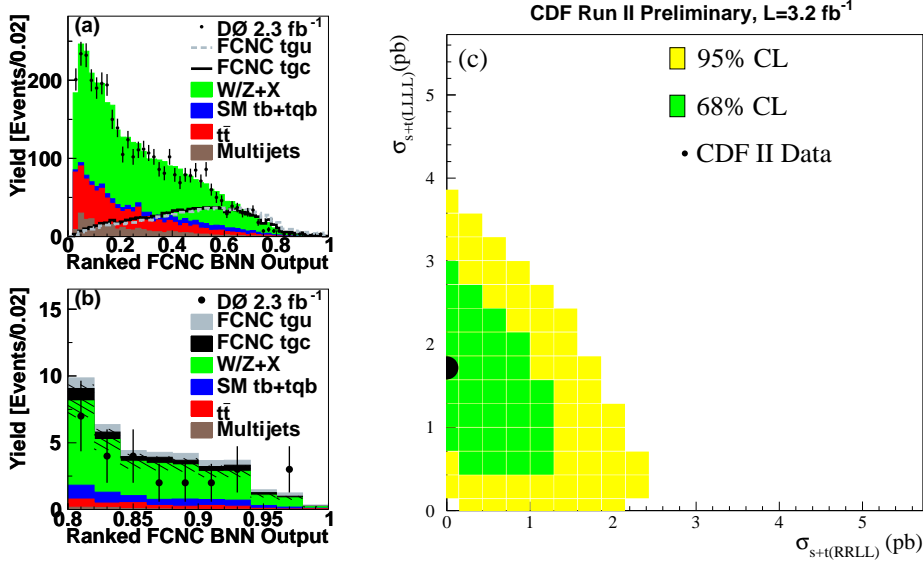


Figure 2: (a) and (b) comparison of the background model to data for the FCNC discriminant summed over all analysis channels, (a) for the whole discriminant range and (b) only the high discriminant region, where the hatched region gives the uncertainty on the background sum. (c) posterior density as a function of the LLLL and RRL coupling cross sections.

### 3 Searches for new physics

The single top quark final state is sensitive to many new physics signatures. The  $s$ -channel final state could receive contributions from a new heavy  $W'$  boson, whereas the  $t$ -channel could receive contributions from flavor-changing neutral current (FCNC) interactions. All single top quark signatures are sensitive to modifications of the top quark coupling to the  $W$  boson and the  $b$  quark.

#### 3.1 Search for $W'$ boson production

Models of new physics that introduce additional symmetries predict the existence of additional heavy charged bosons, generally called  $W'$ . The DØ collaboration performed a search for  $W'$  boson production in 2.3 fb<sup>-1</sup> of data, using the same event selection and background modeling as the single top quark observation analysis. This is the first  $W'$  boson search in the single top quark final state that explores the full parameter space of both SM-like left-handed couplings and right-handed couplings and a mixture of both for the  $W'$  boson. The resulting limits on the  $W'$  boson mass as a function of the two couplings are shown in Figure 1(c). For SM-like left-handed  $W'$  couplings, the limit on the  $W'$  boson mass is  $M(W') > 863$  GeV. For purely right-handed couplings it depends on whether a right-handed neutrino ( $\nu_R$ ) exists and is lighter than the  $W'$  boson, the limit is  $M(W') > 885$  GeV for  $M(W') < m(\nu_R)$  and  $M(W') > 890$  GeV for  $M(W') > m(\nu_R)$ . If both left-handed and right-handed couplings are present, the limit is  $M(W') > 916$  GeV.

#### 3.2 Flavor-changing neutral currents

The  $t$ -channel final state is sensitive to flavor-changing neutral currents via quark-gluon couplings. In FCNC interactions a gluon vertex couples an up quark or a charm quark to the top quark. The rate for these events is large because of the initial state containing two light quarks. The DØ collaboration searched for FCNC interactions in the same dataset as used in

the observation analysis<sup>13</sup>. Two FCNC couplings are considered, to up quarks ( $tgu$ ) and to charm quarks ( $tgc$ ). A Bayesian Neural Network (BNN) is used to separate the FCNC signal from the large backgrounds. The BNN output distribution is shown in Fig. 2(a) and 2(b). The limits on the couplings are  $\kappa_{tgu}/\Lambda < 0.013 \text{ TeV}^{-1}$  and  $\kappa_{tgc}/\Lambda < 0.057 \text{ TeV}^{-1}$ , without making assumptions about the  $tgc$  and  $tgu$  couplings, respectively. The corresponding limits on top quark decay branching fractions are  $\mathcal{B}(t \rightarrow gu) < 2.0 \times 10^{-4}$  and  $\mathcal{B}(t \rightarrow gc) < 3.9 \times 10^{-3}$ .

### 3.3 Top quark polarization

The observation of single top quark production assumes SM-like left-handed couplings of the top quark to the  $W$  boson and the  $b$  quark. The CDF experiment performed a search for production of single top quarks through right-handed couplings. The two specific models under investigation are SM-like left-handed coupling at all four interaction vertices ( $LLLL$ , two for top quark production and two for top quark decay) and right-handed anomalous couplings in top quark production together with left-handed couplings in top quark decay ( $RRLL$ ). The Bayesian posterior probability density as a function of the cross section for single top quark production with these two couplings is shown in Fig. 2(c). The data are consistent with the SM, and the measured polarization is  $\frac{\sigma_{RRLL} - \sigma_{LLLL}}{\sigma_{RRLL} + \sigma_{LLLL}} = -1_{-0}^{+1.5}$ .

## 4 Conclusions

The Tevatron experiments DØ and CDF have each observed single top quark production at the five standard deviation level and have measured the production cross section as well as the CKM matrix element  $V_{tb}$ . The measurements as well as a measurement of the  $t$ -channel production mode are consistent with the SM expectation. Several new physics scenarios have been explored in the single top quark final state and limits have been set on a new  $W'$  boson, on flavor-changing neutral currents, and on anomalous top quark couplings.

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